Off-shore Autonomous Power Supply: Measured performance of the BOLT Lifesaver System and Future Application as a Low Observable Sensor System and Recharge Station

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1. INTRODUCTION

BOLT Lifesaver, pictured in Figure 1, is a *Wave Energy Converter* (WEC) system developed by *Fred. Olsen*. This is an electro-mechanical system for producing electricity from ocean waves, and the system consists of a 16 m wide toroidal floater, three production machines and one electrical conversion package. BOLT Lifesaver was first deployed on the *FabTest* test site on the coast of Falmouth, England on 31. March 2012 and stayed in continuous service for more than two years until the end of April 2014. After the test period in England, BOLT Lifesaver was disassembled and shipped to Hawaii to undergo testing in collaboration with the US Navy. The device was installed on the WETS test site outside Kaneohe, Hawaii on 26. March 2016 and is currently in operation. BOLT Lifesaver is designed as a stand-alone power system with the ability to deliver power to onboard consumers, but also has the ability to export to grid [1]. This paper will present the measured performance at Fabtest, the current deployment at WETS Kaneohe, Hawaii and present the planned future approach and application for the BOLT class WEC system.

Fred. Olsen started with Wave Energy around year 2000, and in 2004 the Wave Energy Converter *Buldra*, built as a platform with multiple point absorbers [2], was launched. Since then, Fred. Olsen has tested out various concepts and built several different prototypes, all based on the point absorber principle. The series of experiences have led to the single body point absorber concept, as realized in *BOLT Lifesaver*. Up to date, Fred. Olsen has successfully operated five different WEC systems in real sea conditions, without having a single serious incident causing system damage or long term down-time.

The main properties for the *BOLT Lifesaver system* are listed in Table 1. The point absorber principle used

Figure 1: *BOLT Lifesaver* on site at the WETS test site outside Kaneohe, Hawaii.

on Lifesaver has been extensively researched and is well described in literature (Falnes et al., 2003, 2012) [3, 4]. Several similar systems have also been deployed by other actors such as the *Seabased* system developed in close collaboration with Uppsala University [5]. The US based *Ocean Power Technologies* has developed the *PowerBuoy*, which is a slack moored dual body point absorber [6]. Similar systems have also been evaluated and tested by the Oregon State University program *SeaBeavl* [7], and has also been realized in systems as *IPS* and *Wavebob* [8]. Hence, the BOLT hull configuration and absorber system can be viewed as proven technology.

The *Power Take-Off* (PTO) system on the other hand is more challenging. Fred. Olsen has spent significant resources on developing a robust, efficient and powerful extraction machinery. The PTO system is realized as an electro-mechanical drive-train based on high ratio carbon belt gears. The PTO system is viewed as the core technology of the BOLT Lifesaver system and is realized as a tension winch system, as shown in Figure 2. The control principle utilized on Lifesaver is based on pas-

Table 1: Lifesaver key parameters

Floater outer diameter	16	m
Floater inner diameter	10	m
Floater height	1.0	m
Mass	55	tons
Number of PTO slots	5	
Currently installed number of PTOs	3	
Damping force per PTO	100	kN
WEC rated export power (5 PTO)	50	kW
WEC rated export power (3 PTO)	30	kW
Generator namepl. capacity per PTO	80	kW

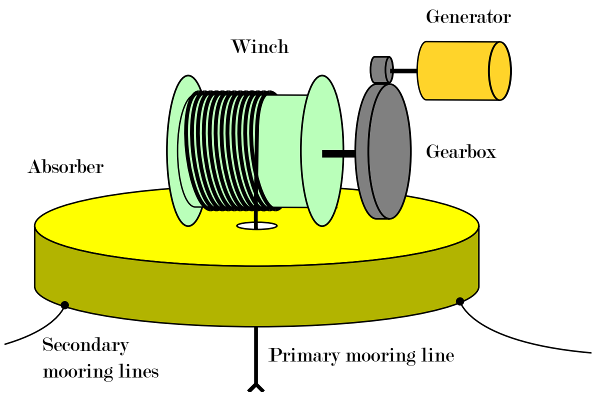

Figure 2: BOLT Wave Energy Converter principle

sive damping, but is heavily influenced by saturation control on both torque and power, in addition to stability control and mechanical protection control. The BOLT Lifesaver system has been described in detail in earlier publications [9].

2. MEASURED PERFORMANCE

BOLT Lifesaver has delivered a substantial amount of data over the last three years of operation. A detailed analysis of the power output performance was presented after one year of operation [10]. This article will focus on the operational aspects of the BOLT Lifesaver system, and presents for the first time the total availability and performance delivered at FabTest. The key performance indicators up to date are listed in Table 2. As BOLT Lifesaver is a stand-alone system, all on-board power consumption must be covered by the produced wave energy. Hence, the system can only be operational when there is enough waves to produce a power surplus. As the FabTest site is situated close to the English channel with frequent periods of calm seas, the potential for production is reduced. As much of the production occurred below rated power, the resulting efficiency fell short of the efficiency potential of 70-80 % at rated power. Nevertheless, due to the all-electric PTO systems capability to maintain power surplus at very low motions, BOLT Lifesaver has demonstrated surplus power production down to 0.4 m Hs. In more energetic wave climates, such as the current deployment at WETS, this gives BOLT Lifesaver the potential to stay continuously in operation.

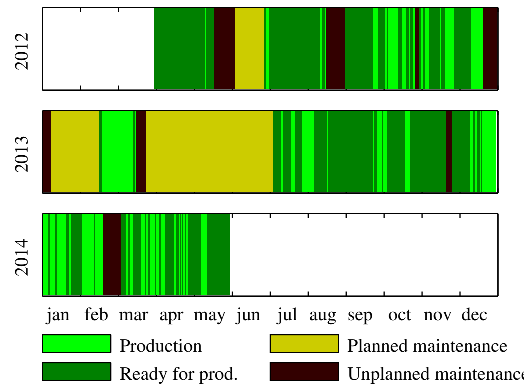

Figure 3: BOLT Lifesaver uptime at FabTest

Table 2: Key performance indicators

Production hours	4 280	h
Electrical energy produced	10 491	kWh
Mechanical energy absorbed	18 654	kWh
Overall efficiency	56.2	%
Average power during production	2.5	kW
Time on site	812	days
One or more PTOs ready	625	days
Longest continuous production	31	days

Since the BOLT Lifesaver system operates with stiff moorings, the generator motion is directly coupled with the wave surface motion. This leads to a very high rate of motion cycles on the mooring system and drive-train, and is a great challenge to component lifetime. While standard winch systems based on ropes or wires usually break down after about 100 000 cycles, BOLT Lifesaver has to handle several million cycles per year. To overcome this, Fred. Olsen has designed a novel winch system that has the potential to operate for several years without maintenance. BOLT Lifesaver was the first device to be launched with this mooring system, and it became clear soon after sea launch that design of this system had to be improved for sustained operation.

During the the first year at FabTest, several minor upgrades and one major upgrade was performed on the primary mooring system. Figure 3 plots the operation mode for the entire test period, and shows the long periods of planned maintenance during the first year to improve the primary mooring system. The major upgrade during spring/summer 2013 greatly improved the up-time, as can be seen in the plot. Table 3 lists the causes for downtime during the test period and demonstrates that, except for the issues related to the primary moorings, BOLT Lifesaver delivers good performance. After the FabTest deployment, a second major upgrade has been performed on the primary mooring system, which will hopefully result in further increased up-time during the WETS test period.

Primary mooring failure	89.5	%
Control system failure	5.6	%
PTO mechanical failure	3.0	%
PTO electrical failure	1.9	%

Table 3: Causes for unplanned maintenance

3. OFF-SHORE POWER STATION

The BOLT class WEC is very well suited for supplying power to off-shore applications, and have the potential to out-compete wind and solar in the 0.1-100 kW range. Below 0.1 kW, PV-panels or batteries have proven to deliver the required performance, and around 100 W seems to be a boundary for small off-shore stations today. Thus, the BOLT technology holds the potential to unlock new applications and technology areas for off-shore based systems such as communication, monitoring and vehicle recharging. Alternatively, the WEC could serve as a stand-alone power plant for surface or sub-sea equipment for military applications, process plants for oil, gas or mining industry.

A very interesting feature with the BOLT technology is the ability to produce power below surface. A shift from the current surface absorber to an underwater buoyant absorber only introduce a small change in the BOLT WEC principle as the core technology, power extraction mechanism and control philosophy stays the same. A submersed system is very interesting for military systems that aim for low observability, and wave energy is one of very few technologies that can deliver power below surface. The ability to produce power below surface has been demonstrated by several other WEC systems [11, 12] and can be regarded as proven technology.

The submersed absorption method that is closest to the current BOLT Lifesaver configuration is the underwater buoyant absorber. This is based on an exposed air volume that is excited by the pressure difference caused by the incident waves. Equation (1) describes the pressure potential p at water depth z, where $\boldsymbol{x}$ refers to the direction of wave propagation, ρ is the water density, g is the gravity constant, a is the wave amplitude, k is the wave number and θ is the wave phase which is linked to the time t. Figure 4 plots the resulting pressure potential at various depths for the wave state of 2.75 m Hs / 6.5 s period (Tz), which is the design wave state for BOLT Lifesaver. Although the figure demonstrates the presence of pressure differential in deeper waters, the most effective power generation would be obtained at lowest possible depth. Firstly, the pressure potential is best here, secondly, the ratio between pressure difference and background pressure decreases with depth and reduce the effect of volumetric difference.

$$p(\boldsymbol{x}, z, t) = \rho g a \cdot e^{kz} \cos\theta \qquad (1)$$

Up to date BOLT Lifesaver has only been operated with tight primary moorings to the PTOs, which limits the operational depth to around 100 m. To overcome this limitation, the stiff mooring can be replaced with a heave-plate that provides counter force based on damping and added mass from the surrounding water. Fred. Olsen has researched extensively on this, and have found that such a configuration can work well with the current PTO design. One of the main goals for the sea trials at Kaneohe test site was to deploy this mooring system, however, due to trouble with obtaining the right permits, the system has to be operated with the usual bottom fixed moorings for all three PTOs. Nevertheless, Fred. Olsen has no reason to question the effects of heave plates, as demonstrated by many other WEC developers, and we are confident that this is a valid replacement. This allows the BOLT Lifesaver technology to be operated at virtually any wave depth as a slack moored system.

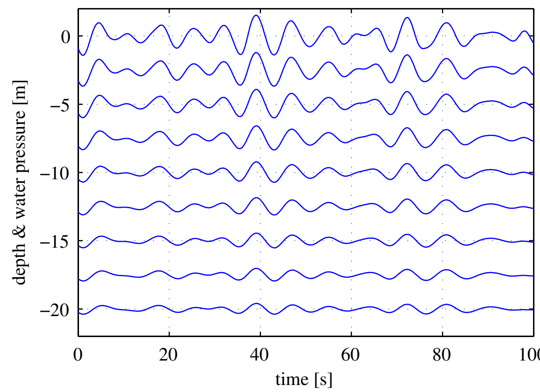

Figure 4: Pressure potential at different depths with 2.75 m Hs. (Pierson-Moskowitz Spectrum)

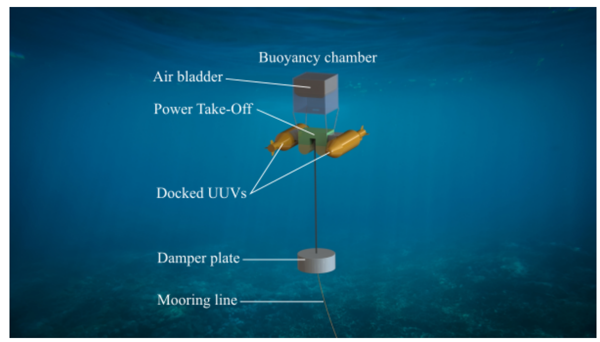

Figure 5: Artistic impression of a fully submersed WEC system recharging two unmanned underwater vehicles.

Figure 5 shows an artistic impression of a submersed recharge station for *Unmanned Underwater Vehicles* (UUVs). A challenge with such a system is the lack of reference to either surface or bottom, which pose a challenge of maintaining the vertical position. The exposed air volume required to absorb the incident wave pressures is naturally unstable and must be actively controlled to maintain equilibrium. Fred. Olsen has investigated this problem through theoretical analysis and simulations, and has identified the boundary conditions required to maintain stable operation. The analysis show that such a system can be designed with high degree of flexibility. A submersed system could be very effective in that it could allow for rapid deployment in any water depth. Both the buoyancy chamber and the heave plate could be realized as a flexible, inflatable bodies, which would result in a very compact design. Realization of such systems will require extensive research and development, and Fred. Olsen is currently seeking applications that can utilize the BOLT system at the current technology level.

4. CONCLUSION

BOLT Lifesaver has demonstrated good performance at the FaB Test test site with an up time of approximately 75%, and has proven the viability of the BOLT technology. The current deployment on the Kaneohe test site will test the performance in an energetic ocean climate, and is expected to demonstrate increased uptime due to improved primary moorings. The future development for the BOLT system is focused towards the application as an off-shore autonomous power plant. The platform may power monitoring and/or communication equipment for commercial, scientific or military use. The technology also has the ability to operate as a completely submersed system, which can be beneficial for certain military applications.

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